**DEVELOPMENT OF A 1 μs, 40 Hz, X-RAY SOURCE***

S. L. Shope, J. M. Jojola, G. Rohwein, and K. R. Prestwich
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-5800

Abstract

We are developing a 1 cm diameter, 1 μs, 300 keV, 1 kA repetitive pulsed electron beam diode to be used in a linear x-ray source. The diode is required to operate from a single pulse mode up to 40 Hz. A single pulse, double x-ray source has been developed and tested. Each source produces a 1 μs electron beam with energies up to 300 keV, 1 kA for each of the two sources. The electron beams impinge on 5 mil tantalum converters to make the x-rays. The x-rays are produced in field emission diodes powered by a single PPT, a pulsed transformer and a capacitive pulse forming network (PFN).

## Introduction

We are developing a x-ray source to be used in imaging experiments using backscattered x-rays. The final source will be a 3 m long linear x-ray source. The source must be able to be sequentially pulsed across its length so imaging can be performed with the backscattered x-rays. Adjacent sources must be a maximum of 4 cm apart to have sufficient resolution for the imaging. Each cathode must fire at a repetition rate of ~40 Hz. To meet these requirements a high current, transformer driven pulsed system has advantages over low current, DC x-ray sources. In the high current pulsed mode about $10^{13}$ photons are produced in a single 1 μs pulse. Each transformer can drive multiple cathodes separated by 1 m. Diodes from other transformers can be placed next to each other and have delayed firings to meet the 4 cm space requirements and allow time between successive cathode firings to process imaging data.

A dual output source has been built and tested in a single pulse mode. A pulsed transformer with a capacitive and inductive pulse forming network provides a high voltage pulse to the two electron beam diodes. Each of the diodes uses field emission from a cold cathode to generate a high current electron beam. To produce the x-rays, a high Z material, such as tantalum, is used as both an anode and a x-ray converter.

## The PPT

The PPT design is similar to several successful systems built by Sandia.[1] The PPT driver consists of a positively charged, spark-gap switched, 1 μs, capacitive PFN coupled to a 10 X auto transformer. The system was designed to drive a matched load of 100 ohms. The PFN is made of ten, parallel, 30 kV, 0.3 μF capacitors interconnected with 40 nH single-loop inductors. The capacitors are DC charged with a 30 kV power supply. The capacitors are switched by a pressurized three electrode spark gap with the mid-plane electrode the trigger electrode. The mid plane is resistively held at a V/2 potential. To minimize the size and weight of the transformer a design was chosen that uses spiral copper strip windings and ferrite bars. Strip wound transformers with partial ferrites cores have high coupling coefficients and reduce the size and weight of the unit. Structurally, the transformer windings are housed in a 16" OD fiberglass cylinder. The ferrite, coil windings, and grading structures are mounted on another fiberglass support structure with nylon insulators on each end. To minimize the weight of the transformer the center cylinder has air in it while the outer section containing the windings is vacuum impregnated with insulating oil. The output of the transformer feeds through an oil filled bushing on a single RG 220 coaxial cable. The cable goes into another oil filled container where it is spliced to two RG 220 cables, one for each diode. The transformer was tested at full voltage into a 100 ohm resistive load. It was run at a repetition rate of 20 Hz for a few hundred shots during the checkout phase. The prototype transformer was used in a single pulse mode for all of the diode and source development work described in the following sections.

## X-Ray Production

The University of Florida has determined that 80 keV x-rays are optimum for imaging with backscattered x-rays.[2] The production of x-rays can be qualitatively described by Kramer's approximation. Kramer's approximation assumes the concave upward x-ray spectrum can be approximated by a straight line. It further assumes that the efficiency of conversion of electrons to x-rays is proportional to the electron energy, $E_b$, and that self-absorption of x-rays in the converter is negligible. If a linear x-ray spectrum is drawn for various electron energies and the number of joules in the electron beam is held constant the spectra all pass through a common point on the vertical intensity axis. The horizontal axis is the x-ray energy, $E_x$, and is proportional to the electron energy. The area of the triangle is the total energy radiated per joule of electron beam and is defined the efficiency, ε. The height of the vertical axis must remain a constant. Simple geometric considerations give an expression for the efficiency of:

$$\varepsilon = 0.1E_x[1-0.5(E_x/E_b)].$$

The energies $E_x$ and $E_b$ are in MV. This implies 200-300 keV peak electron beam energies are needed for the source to have sufficient quantity, $10^8$, of 80 keV x-rays. A Monte Carlo run was made with the TIGER code to look at the x-ray production.[3] The results are given in Table 1. The x-ray production at these energies is nearly isotropic.

Table 1. Calculated x-ray spectrum for 300 keV electrons impinging on a tantalum converter.

| $E_{max}$ (keV) | $E_{min}$ (keV) | Photons/pulse |
|---|---|---|
| 300 | 285 | 1.68E+11 |
| 270 | 255 | 6.31E+11 |
| 240 | 225 | 1.16E+12 |
| 210 | 195 | 1.86E+12 |
| 180 | 165 | 2.80E+12 |
| 150 | 135 | 4.17E+12 |
| 120 | 105 | 5.93E+12 |
| 90 | 75 | 7.84E+12 |
| 60 | 45 | 3.71E+13 |
| 30 | 15 | 8.76E+13 |

*This work was sponsored by the US Army under contract DE-AC04-76DP00789.

| **Report Documentation Page** | | | *Form Approved OMB No. 0704-0188* |
|---|---|---|---|
| Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. | | | |
| 1. REPORT DATE<br>**JUN 1993** | 2. REPORT TYPE<br>**N/A** | | 3. DATES COVERED<br>**-** |
| 4. TITLE AND SUBTITLE<br>**Development Of A 1 J.S, 40hz, X-Ray Source Development** | | | 5a. CONTRACT NUMBER<br>5b. GRANT NUMBER<br>5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | | | 5d. PROJECT NUMBER<br>5e. TASK NUMBER<br>5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**Sandia National Laboratories P.O. Box 5800 Albuquerque, NM 87I85-5800** | | | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | | | 10. SPONSOR/MONITOR'S ACRONYM(S)<br>11. SPONSOR/MONITOR'S REPORT NUMBER(S) |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT<br>**Approved for public release, distribution unlimited** | | | |
| 13. SUPPLEMENTARY NOTES<br>**See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License** | | | |
| 14. ABSTRACT<br>**We are developing a I em diameter, I f.lS, 300 keV, I kA repetitive pulsed electron beam diode to be used in a linear x-ray source. The diode is required to operate from a single pulse mode up to 40 Hz. A single pulse, double x-ray source has been developed and tested. Each source produces a I f.lS electron beam with energies up to 300 keV, I kA for each of the two sources. The electron beams impinge on 5 mil tantalum converters to make the x-rays. The x-rays are produced in field emission diodes powered by a single PPT, a pulsed transformer and a capacitive pulse forming network (PFN).** | | | |
| 15. SUBJECT TERMS | | | |

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **SAR** | **4** | |

There is a total of $10^{13}$ 80 keV photons produced in a single pulse. The source is 15 cm from the 1.0 cm diameter collimator which corresponds to $3.5 \times 10^9$ photons/cm$^2$ or $2.7 \times 10^9$ photons through the collimator.

## Diodes

The objectives of the diode design were to develop a compact rugged diode that would operate at peak voltages of 300 kV and electron beam currents of 1 kA. The electrons would strike a tantalum anode and produce x-rays. The imaging requirements need $10^8$ photons over 12 cm$^2$, at a distance of 30 cm from the collimator. To maximize the x-ray fluence to meet these requirements it was necessary to develop a 1 cm diameter electron beam. This small diameter beam has a rather high current density and can cause thermal heating of the tantalum target and generate a plasma that could prevent repetitive pulse operation. Another design constraint is on the physical size and weight of the diode. In the final application it is necessary to have sources spaced 4 cm apart.

When an anode and cathode are in a high field geometry the electron generation is by field emission from a cold cathode. Microscopic whiskers or other irregularities on the cathode surface go to very high fields and rapidly form a plasma at the cathode surface. It is necessary to maintain a vacuum of $\leq 1 \times 10^{-5}$ torr in the diode to prevent excessive background plasma generation. The cathode plasma can be thought of as a conductor with a work function that is nearly zero. High electron beam currents are generated by electron emission from the cathode plasma. The presence of the cathode plasma reduces the potential of the cathode and increases the potential at the surface of the cathode plasma. The amount of current that will flow in the diode is determined by the modification to the cathode potential. This type of electron emission is referred to as space charge limited diode or current flow. Detailed descriptions of high current electron beams are given in references 4, 5, 6, and 7.

The electron current density, j, for a nonrelativistic space charge limited diode is given by Child's law;

$$j = (2.33 \times 10^{-6})V^{3/2}/d^2 .$$

The voltage, V, is the applied voltage in volts, j is amps/ cm$^2$, and d is the anode-cathode spacing (AK) in cm. When high current electron beams strike an anode a plasma can form on the anode surface. This anode plasma will emit ions in the same manner that the cathode plasma can emit electrons. The velocity of the ions, $v_i$, moving towards the cathode can cause an effective decrease in the AK gap. The equation for j needs to be modified to reflect the time dependence of the AK gap by replacing $d^2$ with $(d-v_it)^2$ where t is the pulse width. The ion velocity is typically a few cm/μs.

The first diode tested was a simple coaxial diode. The inner conductor was a piece of RG 220 with the ground braid removed. The polyethylene insulator of the cable was tapered at a $45^0$ angle down to the 0.6 cm diameter inner conductor. The outer conductor was 10 cm in diameter. The inner copper conductor was used as the cathode. The output pulse was very low in amplitude, 80 kV, and narrow, ~100 ns, indicating either plasma closure in the anode-cathode gap (AK) or insulator flashover. The AK was varied with no improvement in diode performance. This suggested there was a flashover of the polyethylene insulator due to high fields. The outer housing diameter was increased to 20 cm with little or no improvement in the diode performance. Potential plots of the diode were made using an electric and magnetic field design code, EMP program.[7] There were fields in excess of 150 kV/cm at the triple point. The triple point is defined as a region where an insulator and a conductor meet in a vacuum region. Fields as low as 30 kV/cm can cause flashover problems if the electric field is not properly graded.

A diode that was 10 cm in radius with a radial insulator was tried with improved results, but it still showed signs of insulator flashover. Several iterations of diode design through experiments and simulations produced a diode that held up for 1 μs. The successful diode uses a grading ring on the oil side and a shaped cathode holder to reduce the stress on a radial insulator. An equipotential plot of the final design is shown in Fig. 1. Diode waveforms are shown in Fig. 2.

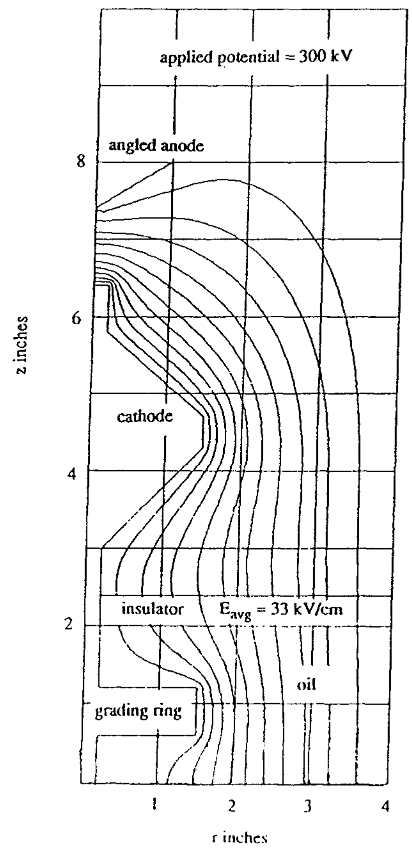
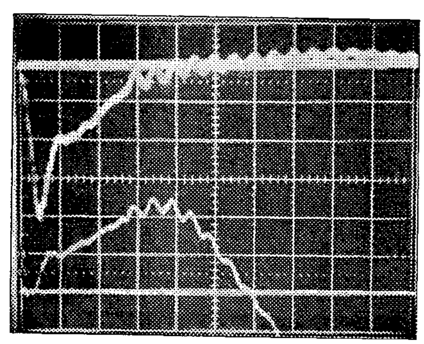



Figure 1. An equipotential plot of the final diode design that uses a radial insulator.



**Voltage: 60 kV/div**
**500 ns/div**

**Current: 2 kA/div**
**500 ns/div**

Figure 2. Radial diode output waveforms.

A one third range, 1 mil, transmission tantalum converter was used as the anode. The x-rays were extracted from the vacuum region through a 1 mil Ti window with a 1 cm diameter collimator. The diode produced a 1 cm diameter x-ray spot, see Fig. 3. The low energy component of the electron beam deposited sufficient energy in the converter to destroy it on a single shot. Debris from the anode also caused a failure of the 1 mil Ti window resulting in a loss of vacuum. A thicker converter, 5 mil, was tried. The thicker target survived with little or no damage but the self absorption of the x-rays was unacceptable. The x-rays from this low voltage electron beam are approximately isotropic. There is little or no advantage to using a thin foil and extracting the x-rays on the beam axis. The thick converter was placed at a $30^o$ angle and a 1 cm diameter collimator and the Ti window was placed at a right angle to the beam axis. The diameter of the angled holder is 2 cm. The window and collimator were located in a flange on the outer edge of the 20 cm diameter vacuum pipe. This put the collimator at a distance of 15 cm from the source. The 1 cm collimator at 15 cm will give a x-ray spot size of 12 $cm^2$ on the ground 30 cm from the source. Figure 4 shows a final diagram of the diode. Diode waveforms and a x-ray pinhole photograph are shown in Fig. 5. The pinhole photograph of the source showed the x-ray source to be slightly elliptical as is expected from the angled source.

A series of 48 shots was fired using a constant charge voltage of 30 kV DC. A PIN diode was placed at the exit of the collimator to measure the x-ray output. During this series the average output voltage was 258 kV with a standard deviation, $\sigma$, of 2.5%. The average current was 1.7 kA with a $\sigma$ of 8.6%. The peak output voltage of the PIN diode had a $\sigma$ of 8.2%. The PIN diode traces were integrated to get the x-ray dose. The dose had a $\sigma$ of 14.4%. Ways to improve the reproducibility of the output are being studied.

The 20 cm diameter diode design is close to meeting the requirements for the final application where the diode packing fraction must allow for 4 cm resolution. A possible configuration is to have diode cylinders adjacent to each other with the electron beams horizontal and the x-rays going down. This would allow a cathode spacing equal to the diode diameter of 20 cm. If another row were placed on top of these with the diodes offset 10 cm this would give a geometry with a source every 10 cm. If there were another identical diode array facing the other and offset by 5 cm this would give a source system that could cover every 5 cm. This arrangement is shown in Fig. 6. Since some diodes are on top of other diodes they are farther away from the ground and will have less intensity on the ground due to the $r^{-2}$ fall off. There will also be a different spot size. These can be corrected by changing the diameter of the collimators and calibrating the detection system for the reduced intensity.

Preliminary results indicate there are more than enough photons at a reduced electron beam energy of 200 keV. This would allow for a reduction in the diode diameter. The maximum radial electric field, $E_m$, for concentric cylinders is given by:

$$E_m = \frac{V}{r \ln \frac{R}{r}} \ .$$

The applied potential is V, R is the outer radius and r is the inner radius. The field for any given r is at a minimum when the ln term is equal to one or R/r = 2.7. If the potential can be reduced from 300 kV to 200 kV the outer radius, R, can be reduced from 10 cm to 6.7 cm and still maintain the same radial fields. This would allow for a $\leq$ 4 cm source spacing.

A double x-ray source was fabricated with a single PPT driving the two diodes. The diodes were mounted on a trolley so that the spacing between the two sources could be varied between 10 cm to 100 cm. The vacuum in the diodes is maintained by a single cryogenic vacuum pump with flexible hoses so that the sources can be moved. The diodes produce simultaneous x-rays. The minimum spacing that can be used between the two sources and still preserve source discrimination will be investigated. This will impact the final design.

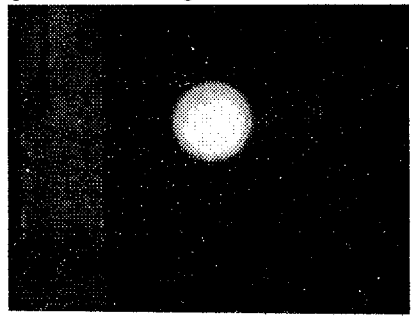



Figure 3. A 1 cm diameter x-ray pinhole photograph.

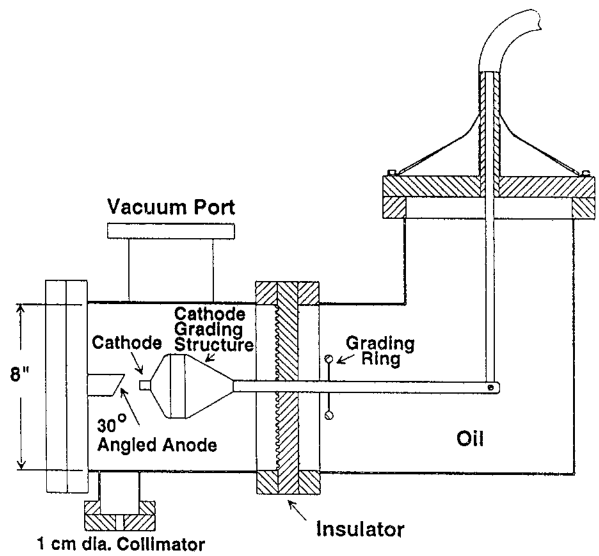
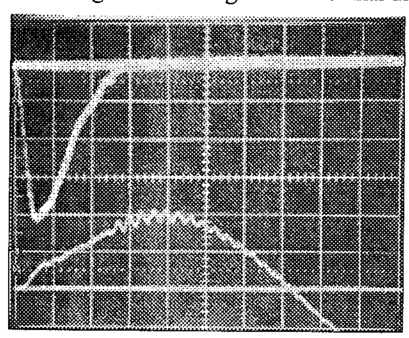



Figure 4. A diagram of the final diode.



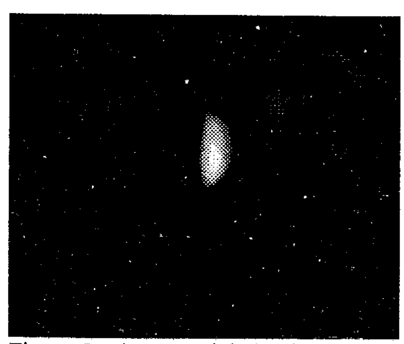




Figure 5. A x-ray pinhole photograph from the final design that is slightly elliptical with a major axis of 1 cm.

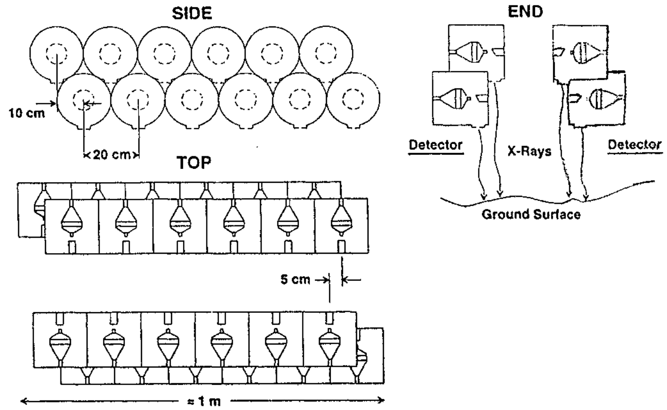



Figure 6. One possible configuration for a 1 m module.

## Conclusion

A single-pulsed diode transformer system has been developed that will produce sufficient x-ray doses for imaging with backscattered x-rays. A double x-ray source has been built and tested in a single pulse mode. The present diode design could be used in a 3 m linear x-ray source that would have a 5 cm pixel size with an excellent chance of reducing that to 4 cm or less.

## References

[1] G. J. Rohwein, R. N. Lawson, and M. C. Clark, " A Compact 200 kV Pulse Transformer System," Proc. of The Eighth IEEE International Pulsed Power Conf., San Diego, CA. June 16-19, 1991.

[2] A. M. Jacobs, Landmine Detection by Backscattered Radiation Radiography, Final Report Prepared for the Army Under Contract DAAK 70-86-K-0016 by The Univ. Florida Dept. of Nuclear Sciences, Gainsville, FL., Jan. 1988.

[3] J. A. Halbleib and T. A. Melhorn, ITS: Integrated Tiger Series of Coupled Electron/Photon Monte Carlo Transport Codes, SAND84-0573, Sandia National Laboratories, Nov. 1984.

[4] J. D. Lawson, The Physics of Charged Particle Beams, Clarendon Press, Oxford, 1977.

[5] R. B. Miller, Intense Charged Particle Beams, Plenum Press, New York, 1982.

[6] S. Humphries, Jr., Charged Particle Beams, John Wiley & Sons, Inc., New York, 1990.

[7] S. Humphries, Jr., Principles of Charged Particle Acceleration, John Wiley & Sons, Inc., New York, 1986.

[8] S. Humphries, Jr., EMP an Electric and Magnetic Field Design Package, Field Precision Co., Albuquerque, NM, 1992.